# A STUDY OF TURBINE PERFORMANCE UNDER COLD WEATHER DRIVEN STABLE ATMOSPHERIC CONDITIONS IN SCANDINAVIA

Carla Ribeiro, Ben Buxton, Simon Cox
*© 2014 Garrad Hassan & Partners Ltd (a DNV GL company)*
*St. Vincent's Works, Silverthorne Lane, Bristol BS2 0QD, UK*
*Tel: +44 (0)117 972 9900 Fax: +44 (0)117 972 9901 www.dnvgl.com*
*email: carla.ribeiro@dnvgl.com, ben.buxton@dnvgl.com, simon.cox@dnvgl.com*

## Abstract

In Winterwind 2013, DNV GL, formerly GL Garrad Hassan, put forward the initial results of an investigation into the effects of atmospheric conditions experienced in Scandinavia on the performance of wind turbines [1]. The authors have demonstrated that highly stable atmospheric conditions are frequently encountered in this region and therefore potential effects on turbine performance should be investigated.

Under stable atmospheric conditions turbulence intensity levels are typically low (< 10%). Thus low turbulence is seen as a proxy for atmospheric stability. These conditions materially differ from the wind flow conditions for which power curves are usually valid. DNV GL has therefore been investigating potential effects on their performance by studying power performance measurement (PPM) data from a number of regions across the world, and in [1], specifically for Scandinavia.

In [1], DNV GL considered 5 IEC compliant PPMs. In this study, the authors have increased the number of PPMs under consideration to 10, from 3 different sites across Sweden, with the aim of creating a body of evidence that is statistically significant. Furthermore, we have also analysed shear as well as turbulence as proxies to stable conditions, and have looked at the influence direction sector selection has in the results.

On average results from the analyses of the additional 5 PPM undertaken in Scandinavia confirm evidences of some underperformance of turbines under low turbulence for sites with average wind speed of 7 m/s or lower. Low turbulence turbine underperformance is higher the lower the mean wind speed and for a site with mean annual wind speed of around 6 m/s this losses will be close to 2% of the annual production. However for average wind speeds higher than 7 m/s there is no significant overall loss or gain of performance under low turbulence.

Results also confirm underperformance of low turbulence power curves in the wind speed ranges from 4 m/s to 8 m/s and overperformance for wind speeds of between 8 m/s and 12 m/s. This suggests that although there is some underperformance in the rising part of the power curve under low turbulence, this can be balanced out by over performance in the knee of the power curve, except for sites where the average wind speed is 7 m/s or lower, given that wind speeds between 8 m/s and 12 m/s are more rare. This will vary from turbine type to turbine type, as rated power and therefore the knee of the power curve is reached at different wind speeds for different turbine types.

Furthermore, site calibrations should be considered not only dependent on direction, but indeed also dependent on climatic conditions such as turbulence and shear, and when that is considered, differences in performance for different climatic conditions will attenuate given that the wind speed at the turbine location is more precisely derived than when considering an overall site calibration.

In light of the turbulence dependent site calibration speed-ups results, we have derived an average low and high turbulence power curve for Scandinavia based on these 10 power curves. These are considered to be representative of the performance of turbines in the climatic conditions of the region. The Scandinavian average turbine performance measurements have been compared with the results obtained by using the theoretical turbine performance model as suggested by the new draft IEC [2].

Although the overall trend of the Scandinavian measurements is similar to the theoretical model, it does not show the same magnitude of performance variation.

## Introduction

In situations where temperature increases with height, the atmosphere is very stable and thus very resistive to vertical motion. Such inversions can be produced in several ways. Low-level inversions (altitudes of a few 100 m) are commonly produced during calm winter nights, as a result of radiative cooling of the surface. A second type of low-level inversion, common in many subtropical regions, is known as the trade-wind, or just trade, inversion. Air in the subtropics is, on average, descending and thus warms adiabatically as it does so this can produce a persistent inversion [3].

Stable atmospheric conditions caused by radiative cooling of the surface are, according to DNV GL experience, common in cold climate regions such as Scandinavia. Snow cover enhances those conditions.

On a local scale snow cover influences the thermal stability of the air immediately above it. Snow cover is a radiative sink. Its high short-wave albedo is combined with a high thermal emissivity which increases the amount of infrared radiation lost near the Earth's surface. The radiative losses are not replaced quickly by heat fluxes from below because of the thermal insulating properties of the snow. It is a particularly good insulator at night when radiative exchange is concentrated in the surface layers of the snow. Surface exchange processes are further modified by the small aerodynamic surface roughness of snow cover which reduces turbulence and vertical transfer [4, 5, 6].

Theory suggests that under low TI turbines underperform in the rising part of the power curve as power depends on turbulence ($P = 1/2\rho(u)^3(1+3TI^2)ACp$). It also suggests that around the knee of the power curve the opposite happens. This is to do with the positive and negative wind speed fluctuations around those wind speed ranges and how they affect the power output [7, 8, 9, 10]. Figure 1 below represents the theoretical performance of a power curve for different turbulence intensities.

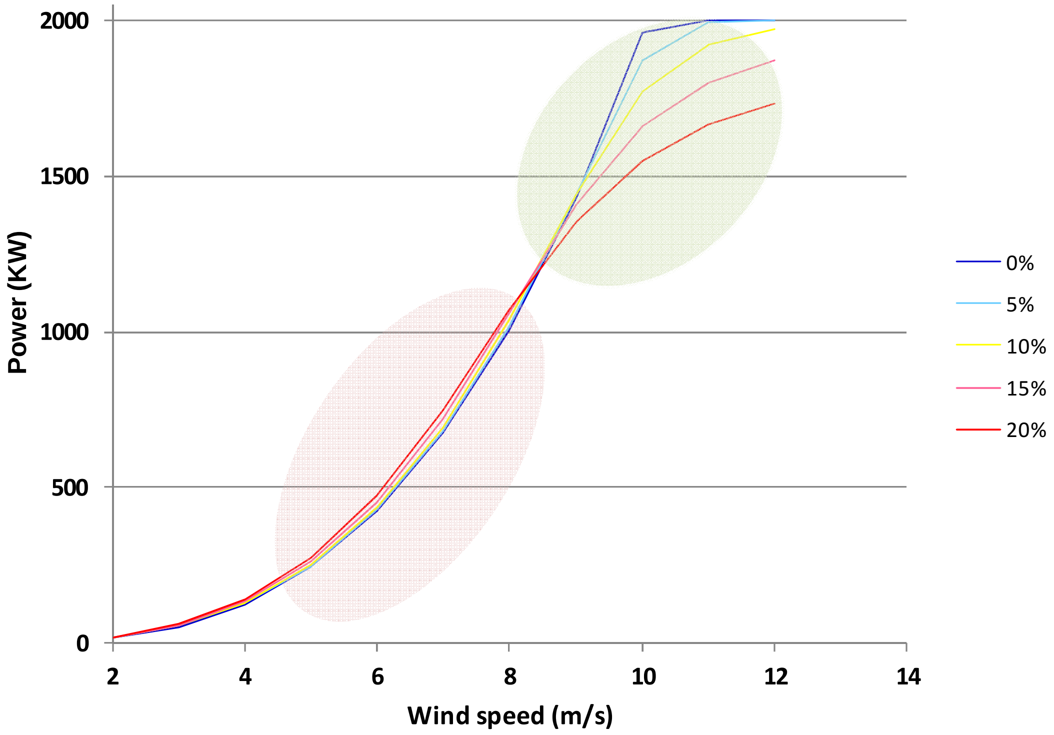


**Figure 1 - Theoretical performance of a power curve for different turbulence intensities. The red ellipse represents the rising part of the power curve, the green ellipse represents the so called knee.**

Under stable atmospheric conditions turbulence levels are typically low (< 10%). Thus low turbulence is seen as a proxy for stable conditions. These conditions materially differ from the wind flow conditions for which power curves are usually valid for.

Previous results [1] showed that when comparing production under low turbulence to high turbulence, there was a loss of performance in the rising part of the power curve, for low turbulence conditions. However, the opposite was true in the wind speed range of 8 m/s to 12 m/s, the so-called “knee” of the power curve. In [1], DNV GL also shows that the site calibration performed as part of the PPM should be dependent on the atmospheric conditions experienced at the test site. The investigation suggests that an improvement in the site calibration procedure, considering different flow correction factors, or more commonly site calibration speed-ups, for different atmospheric conditions, reduces the spread in performance seen under low and high turbulence between individual turbines, and when this was considered, on average, there was no significant overall loss or gain of performance under low turbulence for sites with average annual wind speed above 7 m/s. Such consideration for different atmospheric conditions is in fact proposed in the new draft of the IEC standard 61400-12-1 for the PPM of wind turbines [2].

In this study, we survey a set of IEC standard power curve measurements at sites located across Scandinavia. We analyse the data in search for evidence of lower turbine performance under low turbulence conditions and, based on the results, we will look to review our current model of estimating wind farm energy losses in the Nordic region.

**Methodology**

In this study, data from 10 IEC standard power performance measurements (PPM’s), from 3 different sites across Sweden equipped with a total of 3 different turbine models, have been analysed in order to investigate for underperformance under low turbulence conditions. Site 1 has 5 PPM’s, site 2 has 3 PPM’s and site 3 has 2 PPM’s.

All 10 PPM’s were preceded by a site calibration measurement procedure, during which the reference mast records concurrent data to a site mast located at the location of the future turbine position, for a period of time long enough to obtain sufficient records to establish a reliable correlation between the wind speed at the reference mast and the wind speed at the site mast for non-wake affected direction sectors. The objective of the site calibration is to be able to reproduce the wind speed at the turbine position, during the PPM, with the lowest degree of uncertainty possible. As it is not possible to measure precisely the wind speed at the turbine position during the operational period due to the influence of the turbine itself, this is usually done by placing a hub height reference mast upwind from the turbine at close distance, and applying sector wise flow correction factors, or more commonly site calibration speed-ups, derived during the site calibration procedure, to the wind speed recorded by the reference mast. This is done only to non wake affected sectors that pass certain criteria as defined by the IEC Standard [10].

Usually the site calibration procedure is only undertaken for sites where, due to the site’s topography or surface roughness, the wind speed at the turbine location is anticipated to be sufficiently different to the wind speed at the reference mast enough to bias the PPM results. For flat sites with no significant surface roughness this procedure is usually bypassed.

Data from the site calibrations of the 10 PPM’s has also been analysed here. Figure 2 below shows the periods of site calibration and PPM for each of the 10 turbines.

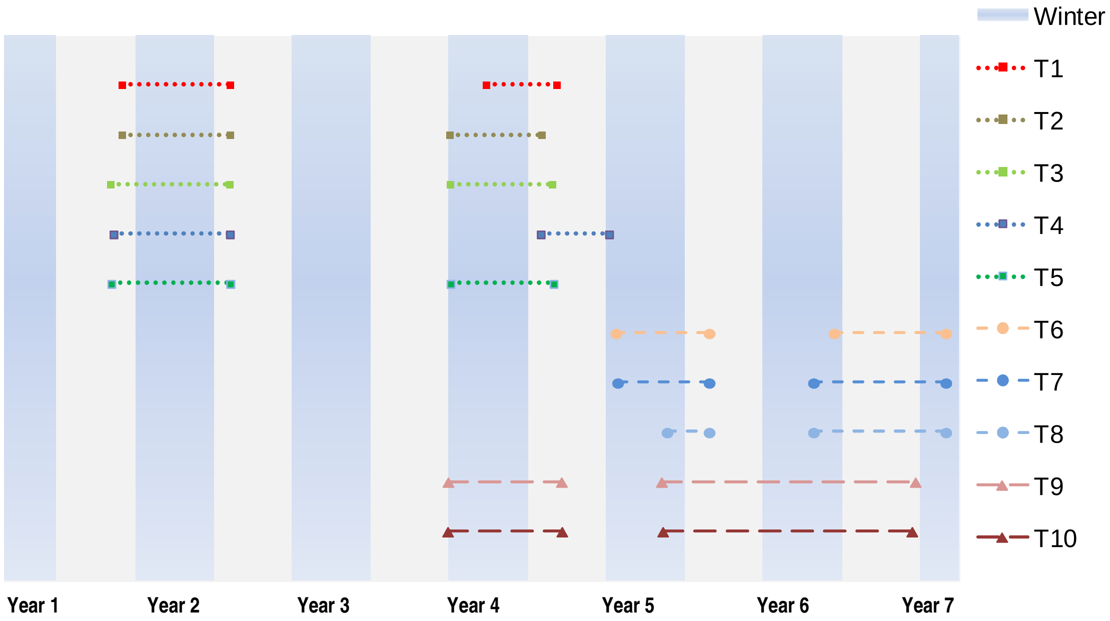


**Figure 2 - Periods of site calibration and PPM for each of the 10 turbines. The first line for each turbine corresponds to the site calibration period and the second to the PPM period.**

For both the site calibration and PPM periods raw wind speed, direction, pressure and temperature data from the masts and additionally power production data from the turbines being tested has been manually inspected in order to detect any erroneous data or data affected by icing. Such data has been removed from the analysis.

All raw wind speed data has been retrospectively scaled by the correct anemometer calibration transfer functions and, where necessary, the Svend Ole Hansen calibration corrections have been applied [11]. Any direction offsets to grid north have also been adjusted.

Wind speed data has been corrected for the site air density according to the IEC Standard [10], on a record by record basis.

For both the site calibration and PPM periods, both the site masts and the reference masts have been equipped with two different types of first class anemometers paralleled installed at hub height. Data from the main anemometer has been considered for the analysis at all sites.

Data for the site calibration period for each of the 10 PPM's has been analysed and flow correction factors (site calibrations or site calibration speed-ups) have been derived for each of the 10 degree sectors deemed suitable [1] according to the IEC Standard [10]. These have been applied to the reference mast data for the corresponding direction sectors in order to derive the wind speed at the turbine location for the PPM's periods. Power output data for periods of time with turbulence intensity <10% (low TI) and turbulence >10% (high TI) have been divided and used to derive power curves for low and high turbulence for each of the 10 turbines under consideration. The relative difference between the performances under each climatic condition has been derived.

The performance difference between low and high turbulence for each of the 10 turbines has been found for a range on common average annual wind speeds in Scandinavian sites Overall power output for each of the 10 low and high TI power curves for Weibull distributions with average wind speeds of 6 m/s, 7 m/s and 8 m/s has been calculated. Overall power output resulting from the low turbulence power curves has been divided by the overall power output resulting from the corresponding high turbulence power curves.

---

[1] Wake-free from neighbouring turbines and distortion-free from topographic, obstacle and mast effects.

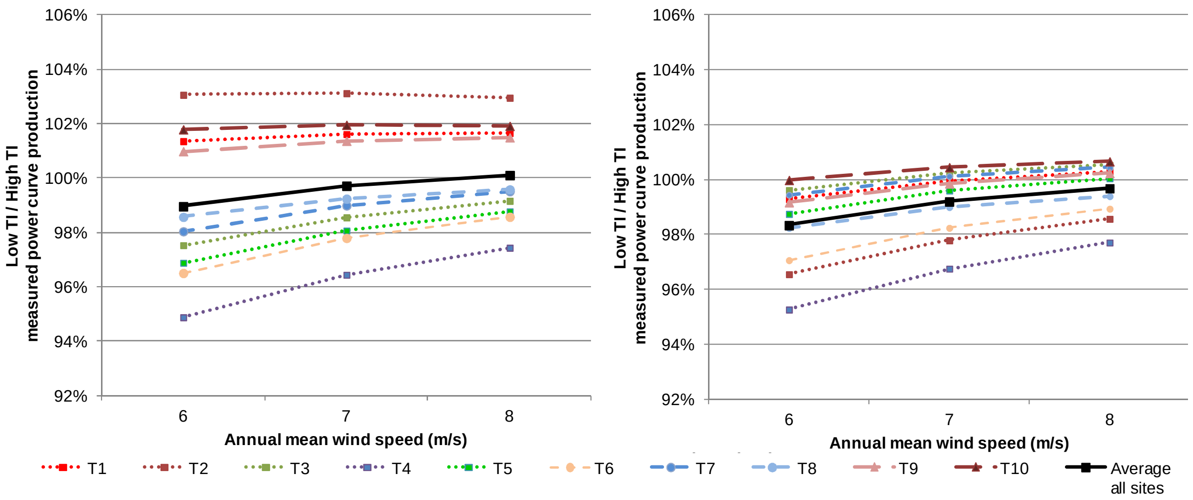
The dependency of site calibration speed-ups with turbulence and shear has been investigated for 3 of the 10 site calibrations, one per site. Site calibration coefficients per 10 degree sectors and for turbulence intensities <10% and >10% have been derived, and these have been applied to the PPM reference data wind speed using the same method as described above.

The same comparison between low and high turbulence power curves and overall power output has been undertaken, now using the turbine wind speed resulting from the direction and turbulence dependent site calibration, using the same methods as for the overall direction site calibrations as described above. The performance difference between low and high turbulence for each of the 10 turbines are compared with the ones obtained using direction dependent site calibrations only.

The average power curves for low and high TI over all 10 turbines were found, for results using site calibration speed-ups dependent on turbulence. The Scandinavian average turbine performance has been derived and compared with the results obtained by using the theoretical turbine performance model as suggested by the new draft IEC [2].

## Results

Overall low turbulence power output divided by high turbulence power output for each of the 10 power curves for Weibull distributions with average wind speeds of 6 m/s, 7 m/s and 8 m/s are shown below for all of the 10 turbines when using a site calibration only dependent on direction in Figure 3, and in Figure 4 when using site calibrations dependent on direction and turbulence.



**Figures 3 and 4 - Difference in power output for low divided by high turbulence conditions, given for overall directional flow correction factors (left) and site calibration speed-ups split by turbulence (right).**

Figure 3 shows that, there is a high variety of results on a turbine by turbine basis, on average, there is evidence of some underperformance of turbines under low turbulence conditions for annual wind speeds below 7 m/s. Figure 4 shows a narrowing of the variety of results per turbine, demonstrating the influence that turbulence dependent site calibrations have in deriving a precise wind speed at the turbine location and therefore correctly analysing the turbine performance. On average results in Figure 4 confirm evidences of some underperformance of turbines under low turbulence for annual wind speeds below 7 m/s.

Figure 5 below shows turbine 6 measured power curve for high and low TI conditions. As the theoretical model predicted, there is a loss of performance under low TI in the rising part of the power curve, and a gain in the knee. The magnitude of variation however is not as high as the model predicts.

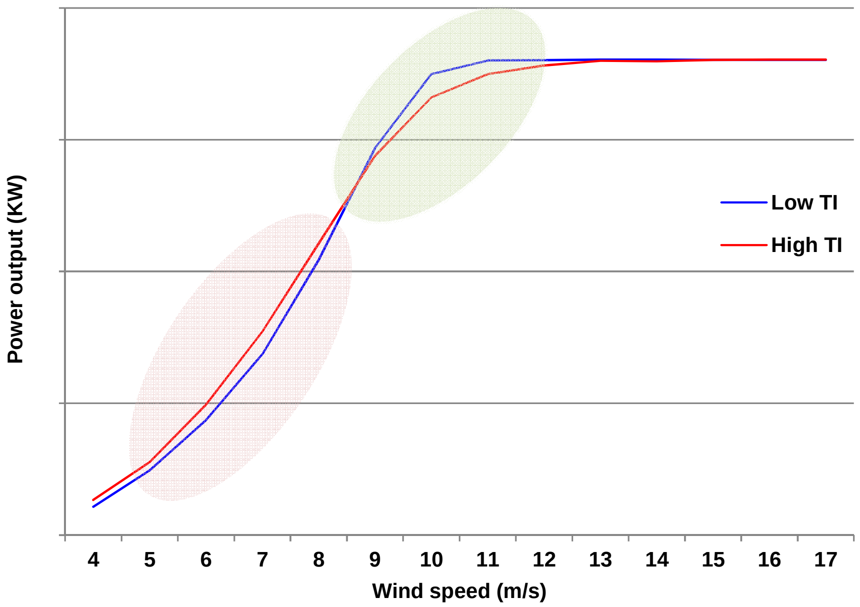
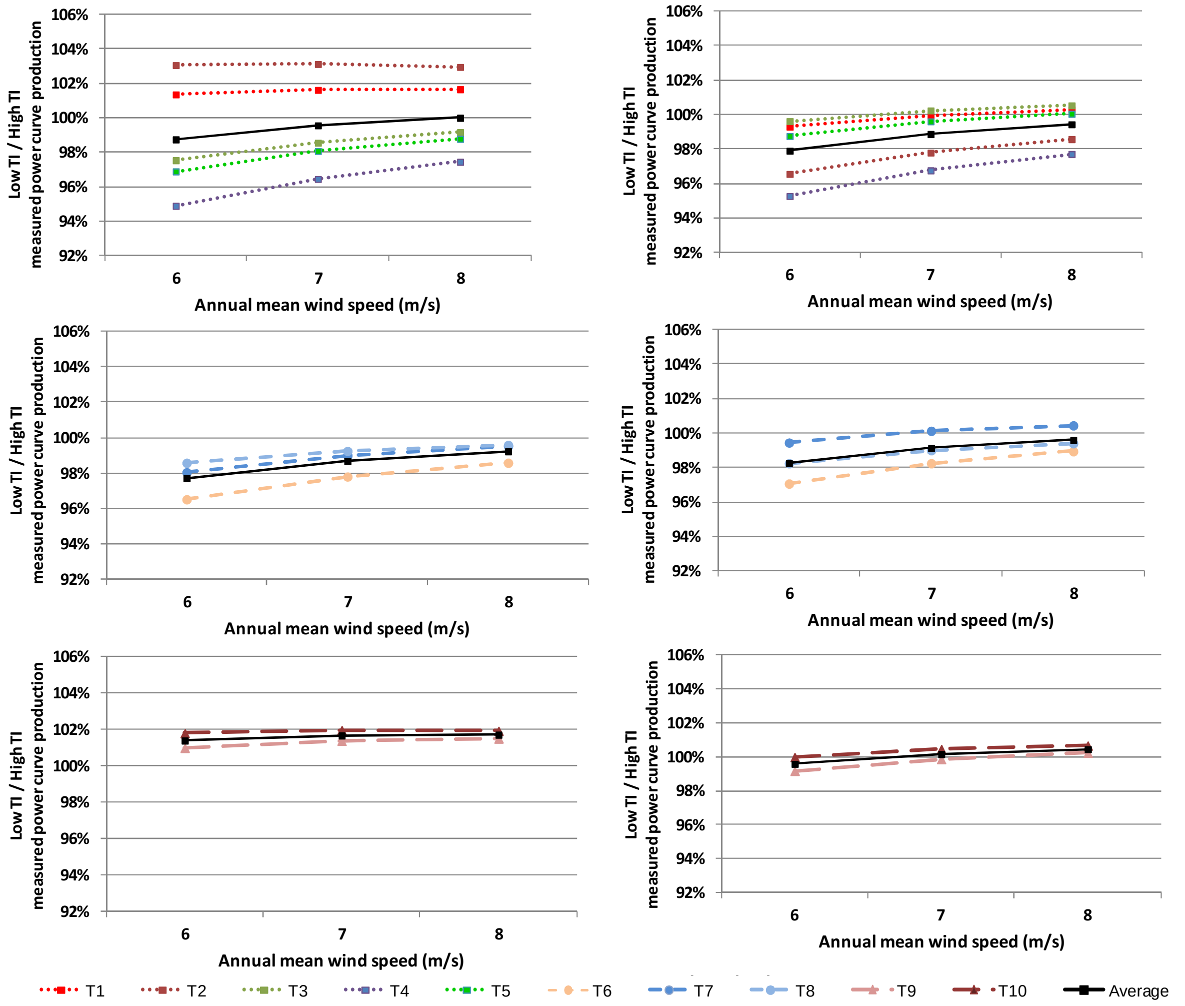


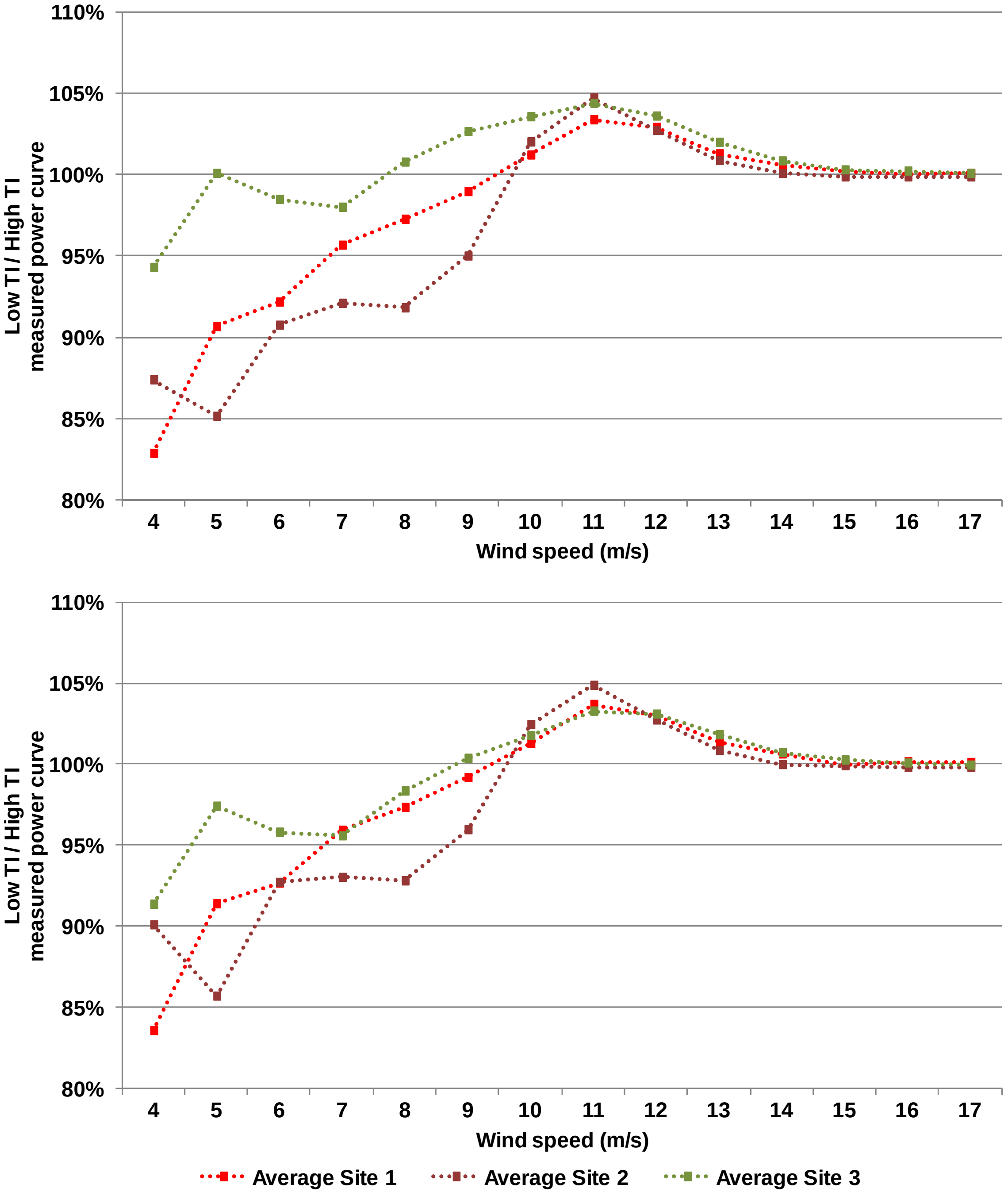
**Figure 5 – Turbine 6 measured power curve for high and low TI conditions. The red ellipse represents the rising part of the power curve, the green ellipse represents the so called knee.**

Figures 6 to 11 below show the same results as figures 3 and 4 divided by site. From these, differences are seen on turbine performance and turbulence dependent site calibrations on a site by site basis, which suggests that turbine performance is influenced by site specific climatic conditions, period of measurements and the frequency of stable conditions during that period, topography and turbine type.



**Figures 6 to11 - Difference in power output for low divided by high turbulence conditions, given for overall site calibrations (left) and site calibrations split by turbulence (right); top Site 1, middle Site 2, bottom Site 3.**

For all the figures above it is possible to see that low turbulence turbine underperformance is higher the lower the mean wind speed. In Figures 12 and 13, below show the difference in power production between low and high turbulence power curve for wind speed bins between 4 m/s and 17 m/s, for the average of the turbines of each site. Figure 12 presents results when considering only direction dependent site calibration speed-ups and Figures 13 shows the same when considering direction and turbulence dependent site calibrations. All graphs show some underperformance of low turbulence power curves in the wind speed ranges from 4 m/s to 8 m/s, the so called rising part of the power curve. However, for wind speeds of between 8 m/s and 12 m/s, the so called “knee” of the power curve, over performance of the low turbulence power curve is evident. This suggests that although there is some underperformance in the rising part of the power curve under low turbulence, on average this is partly balanced out by over performance in the knee of the power curve. This also explains why for lower average annual wind speeds the underperformance seems more evident, as wind speeds in the range of 8 m/s to 12 m/s are less frequent in such sites and therefore the compensation of underperformance in the knee is lower.



Figures 12 and 13 - Difference between low and high turbulence power curve for wind speeds between 4 m/s and 17 m/s, for the average of the turbines of each site. Overall site calibrations (top) and site calibrations split by turbulence (bottom).

As in the previous plots, these plots also show a narrowing of the difference between low and high turbulence performance when considering turbulence dependent site calibrations. This suggests that site calibrations should be considered not only dependent on direction, but indeed also dependent on climatic conditions such as turbulence and shear, and when that is considered, differences in performance for different climatic conditions will attenuate given that the wind speed at the turbine location is more precisely derived than when considering an overall site calibration by direction only. This is that much relevant at sites where stable atmospheric conditions are frequent given the strong stratification of the atmosphere and the substantially different speed-ups between reference mast and turbine location as Figure 14 below shows for the location of Turbine 2, even for the PPM's selected direction sectors. This also emphasises the need to undertake site calibration at any site where stable atmospheric conditions are frequent, given the higher than usual variation in wind speeds across small horizontal distances, even when topography and roughness are not a factor.

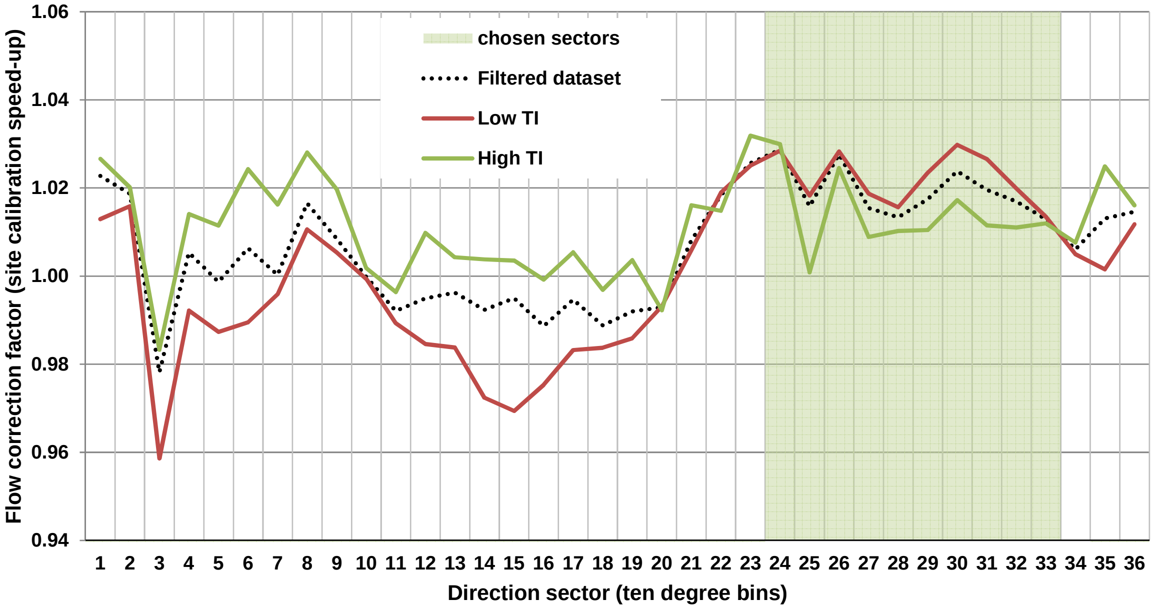


Figure 14 – T1 site calibration speed-ups per sector for, overall, high and low TI conditions

When considering that in the Scandinavian region stable conditions are mainly driven by cold weather and emphasised by snow cover, not only the absolute difference in speed ups between stable and neutral to unstable conditions is relevant for PPMs, but also the difference in frequency of those conditions during the site calibration period and the PPM period. Should these be significantly different, due to being undertaken in different periods of the year, than an overall site calibration found during the summer time can be significantly biasing the PPM wind speed data taken during the winter and vice-versa. Figure 1 above shows the period of the year in which the site calibration and the PPM measurements were undertaken for each of the 10 turbines. Figure 15 below shows the difference in occurrence of high TI conditions between those two periods for each turbine. As expected, turbines in which the difference in frequency of stable conditions between the site calibration and PPM period is higher, combined with the higher difference in low and high TI site calibration speed-ups, are also the turbines where biggest changes in low versus high turbulence performance are found when applying turbulence dependent site calibrations over overall ones.

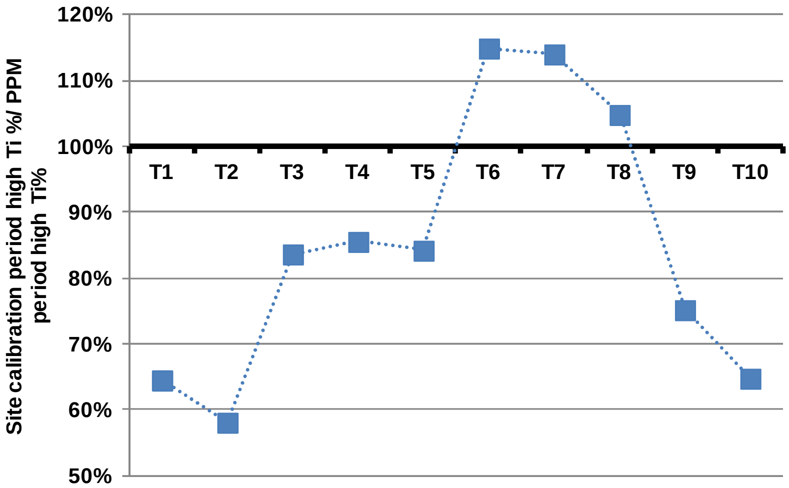


Figure 15 – Difference in occurrence of high TI conditions between site calibration PPM period for each of the 10 turbines

A possible solution for this is to undertake both the site calibration and the PPM during the same months of the year. Another solution is to consider a site calibration not only dependent on direction but also on climatic conditions. The second method is preferred given that frequency of certain climatic conditions over others will also vary between the same seasons in different years.

Figure 16 below shows the variation of site calibration speed-ups with turbulence intensity and shear at one of the 10 turbines.

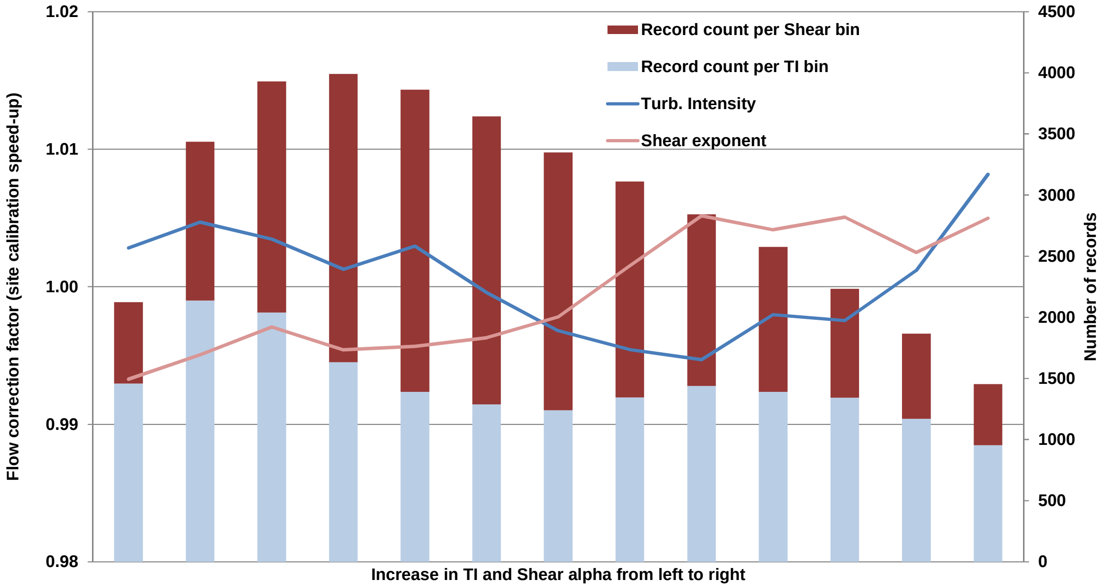


**Figure 16 – Variation of site calibration speed-ups with turbulence intensity and shear at T9**

When considering only the directions deemed suitable for site calibration according to the IEC Standard [10], site calibration varies more with turbulence and shear than it does with direction. Turbulence and shear seem to impact site calibration in the same order of magnitude and are inversely correlated. High shear and low turbulence are usually related to stable conditions, thus meaning that when selecting either high shear or low turbulence, one is selecting broadly the same climatic conditions. For the purposes of this study we have selected turbulence as a proxy for stable conditions given the slightly higher and more consistent variation of site calibration magnitude with turbulence than shear and previous use of such parameter in other studies [1]. However, for PPM, purposes it is recommended to derive matrices of site calibration correlations per bin of direction and the next most correlated parameter which the site calibration varies by, for example turbulence intensity as considered here or wind shear.

Finally, based on turbulence dependent site calibration speed-ups results, the Scandinavian average turbine performance has been derived and compared with the results obtained by using the theoretical turbine performance model as suggested by the IEC [2]. Figure 17 below shows that both the theoretical model and the measurements present an underperformance for the rising part of the power curve and an overperformance for the knee of the power cuve. Although the theoretical model suggests a higher peak than the measured data demonstrates. For the range of wind speeds in the rising part of the power curve, the theoretical model seems to suggest a loss no lower than 5% whilst the Scandinavian measurements suggest it could be lower below around 6 m/s and about the same order of magnitude between 7 m/s to 9 m/s.

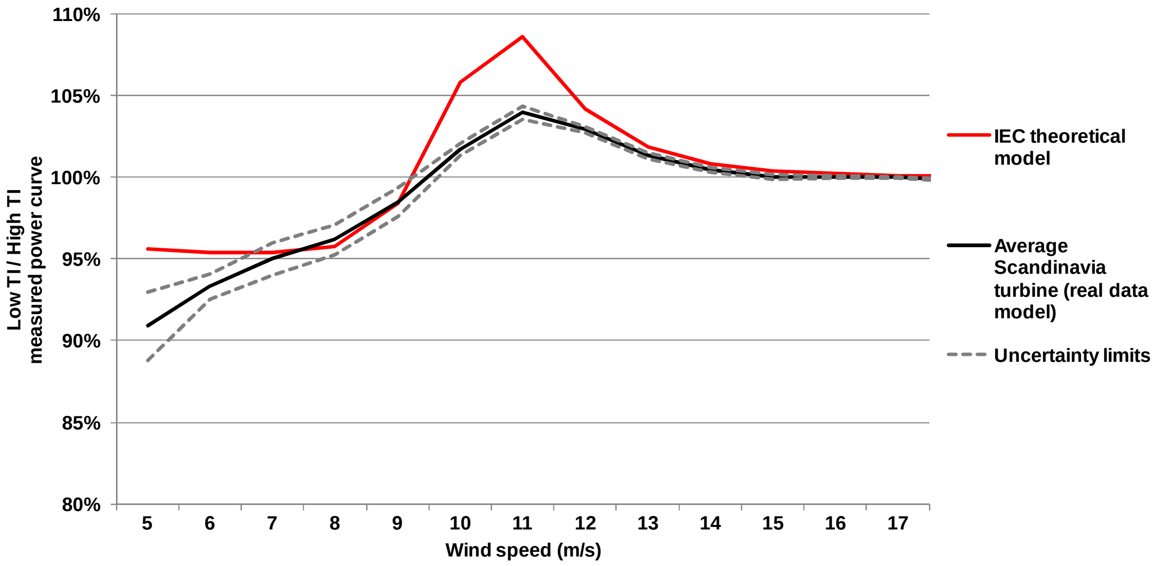


**Figure 17 – Comparison between IEC theoretical model with the Scandinavian average turbine performance**

## Conclusions

On average results from the analyses of 10 PPM undertaken in Scandinavia confirm evidences of some underperformance of turbines under low turbulence stable conditions. Low turbulence turbine underperformance is higher the lower the mean wind speed.

Results show some underperformance of low turbulence power curves in the wind speed ranges from 4 m/s to 8 m/s, the so called rising part of the power curve. However, for wind speeds of between 8 m/s and 12 m/s, the so called “knee” of the power curve, an over performance of the low turbulence power curve is evident. This suggests that although there is some underperformance in the rising part of the power curve under low turbulence, on average this is partially balanced out by over performance in the knee of the power curve, except for sites where the average wind speed is 7 m/s or lower, given that wind speeds between 8 m/s and 12 m/s are more rare for those sites. This will vary from turbine type to turbine type, as rated power and therefore the knee of the power curve is reached at different wind speeds for different turbine types.

Site calibrations should be considered not only dependent on direction, but indeed also dependent on climatic conditions such as turbulence and shear, and when that is considered, differences in performance for different climatic conditions will attenuate given that the wind speed at the turbine location is more precisely derived than when considering an overall site calibration. This is that much relevant at sites where stable atmospheric conditions are frequent given the strong stratification of the atmosphere and the substantially different speed-ups between reference mast and turbine location. This also emphasises the need to undertake site calibration at any site where stable atmospheric conditions are frequent, given the higher than usual variation in wind speeds across small horizontal distances, even when topography and roughness are not a factor.

Not only the absolute difference in speed ups between stable and neutral to unstable conditions is relevant for PPMs, but also the difference in frequency of those conditions during the site calibration period and the PPM period. Should these be significantly different, due to being undertaken in different periods of the year, than an overall site calibration found during the summer time can be significantly biasing the PPM wind speed data taken during the winter and vice-versa.

A possible solution for this is to undertake both the site calibration and the PPM during the same months of the year. Another solution is to consider site calibration correlation coefficients not only dependent on direction but also on climatic conditions and where such frequency varies with seasonality. The second method is preferred given that frequency of certain climatic conditions over others will also vary between the same seasons in different years.

Turbulence and shear seem to impact site calibration in the same order of magnitude and are inversely correlated. High shear and low turbulence are usually related to stable conditions, thus meaning that when selecting either high shear or low turbulence, one is selecting broadly the same climatic conditions. However, for PPM, purposes it is recommended to derive matrices of site calibration correlations per bin of direction and the next most correlated parameter which the site calibration varies by, for example turbulence intensity as considered here or wind shear.

Based on turbulence dependent site calibration speed-ups results, the Scandinavian average turbine performance as resulted from the measurements has been derived and compared with the results obtained by using the theoretical turbine performance model as suggested by the IEC [2]. Both the theoretical model and the measurements present an underperformance for the rising part of the power curve and an overperformance for the knee of the power cuve.  Although the theoretical model suggests a higher peak than the measured data demonstrates. For the range of wind speeds in the rising part of the power curve, the theoretical model seems to suggest a loss no lower than 5% whilst the Scandinavian measurements suggest it could be lower below around 6 m/s and about the same order of magnitude between 7 m/s to 9 m/s.

It can be therefore concluded that although the overall trend of the Scandinavian measurements is similar to the theoretical model, it does not show the same magnitude of performance, as it would be expected for real world data.

On average results from the analyses of the additional 5 PPM undertaken in Scandinavia confirm evidences of some underperformance of turbines under low turbulence for sites with average wind speed of 7 m/s or lower. Low turbulence turbine underperformance is higher the lower the mean wind speed and for a site with mean annual wind speed of around 6 m/s this losses will be close to 2% of the annual production. However for average wind speeds higher than 7 m/s there is no significant overall loss or gain of performance under low turbulence.

**References**

[1] Ribeiro C., Cox, S., Lindahl, S., 2013. “An investigation into turbine performance under cold weather driven stable atmospheric conditions in Scandinavia”. Winterwind Conference, Sweden, 2013.

[2] IEC 61400-12-1 "Wind turbines Part 12-1: Power Performance Measurement of Electricity Producing Wind Turbines". Draft second edition.

[3] John Marshal, “Physics of Atmosphere and Oceans”, Lecture notes, Chapter 4 “Convection”, MIT, 2004/2005.

[4] T. D. Davies, “Snow and Ice Covers: Interactions with the Atmosphere and Ecosystems” (Proceedings of Yokohama. Symposia J2 and J5, July 1993), Climatic Research Unit, University of East Anglia, IAHS Publ. no. 223, 1994.

[5] D.A. Robinson, “Snowcover as an indicator of climate change. In: Large Scale Effects of Seasonal Snow Cover” (ed.by B. E. Goodison.R. G. Barry & J. Dozier) (Proc. Vancouver Symp., August 1987), 15-25. IAHS Publ. no. 166, 1987.

[6] J. Cohen & D. Rind, “The effect of snow cover on climate”, J. Climate 4, 689-706, 1991

[7] Wagner, R, Courtney, M, Larsen, TJ & Schmidt Paulsen, U. 2010, "Simulation of shear and turbulence impact on wind turbine performance". DTU. Denmark. Forskningscenter Risoe. Risoe-R, no. 1722(EN)

[8] Albers, Axel, et al. 2007. "Influence of meteorological variables on measured wind turbine power curves." Proceedings of EWEC 2007.

[9] Albers, A. 2010. "Turbulence and Shear Normalisation of Wind Turbine Power Curve." Proceedings of EWEC 2010.

[10] IEC 61400-12-1 "Wind turbines Part 12-1: Power Performance Measurement of Electricity Producing Wind Turbines". Draft second edition.

[11] “Wind tunnel calibration of cup anemometers – reduced uncertainties, Revision no.1”, Svend Ole Hansen, April 2012.